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Modification of the Fosberg fire weather index to include drought

Scott L. Goodrick

Florida Division of Forestry, 3125 Conner Blvd., Tallahassee, FL 32399-1650, USA; present address: USDA Forest Service, 320 Green Street, Athens, GA 30602, USA. Telephone: +1 706 559 4237; email: sgoodrick@fs.fed.us

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Abstract. The Fosberg fire weather index is a simple tool for evaluating the potential influence of weather on a wildland fire based on temperature, relative humidity and wind speed. A modification to this index that includes the impact of precipitation is proposed. The Keetch-Byram drought index is used to formulate a 'fuel availability' factor that modifies the response of the fire weather index. Comparisons between the original and modified indices are made using historical fire data from the Florida Division of Forestry. The addition of the fuel availability factor helps increase the utility of the fire weather index as it offers an improved relationship between the index and area burned.

Additional keywords: Florida; Keetch-Byram drought index; fire danger.

Introduction

The Fosberg (1978) Fire Weather Index (FFWI) was designed as a supplement to the once-daily fire danger calculations provided by the 1972 National Fire Danger Rating System (Deeming *et al.* 1972). NFDRS is designed to reflect the near upper limit of potential fire behavior that may occur in a rating area on a given day based on average worst-case conditions: mid-afternoon weather conditions, mid-slope on south or south-west aspects. The FFWI is basically a non-linear filter of meteorological information (temperature, relative humidity and wind speed) that provides land managers with a useful tool for interpreting the impacts of small-scale/short term weather variations on fire potential. Land managers can calculate the FFWI using hourly observations from all available weather stations to evaluate the spatial and temporal evolution of the weather component of the fire environment.

The simple structure of the FFWI makes the index a good match for calculation from the output from numerical weather prediction models. Such models are capable of producing weather data on an hourly basis at resolutions of several kilometers. Forecasts of the FFWI are currently provided at a variety of temporal and spatial scales by the Pacific Northwest Regional Modeling Consortium, the Florida Division of Forestry, and the Experimental Climate Prediction Center at Scripps Institute of Oceanography. While the use of numerical model data highlights the above mentioned strength of the FFWI, the FFWI does not take full advantage of all the weather information provided by these models or more traditional observing systems.

The omission of precipitation prevents the FFWI from capturing spatial variations in fire potential due to spatial variability in rainfall amounts. This omission can be very important in a region such as Florida where rainfall during the fire season typically comes from local weather events (e.g. thunderstorms along a sea breeze front) that provide high spatial variability in both rainfall coverage and amount. This study modifies the FFWI by adding a 'fuel availability' factor that accounts for recent rainfall and the evaporation of that rainfall. This fuel availability factor is based on the Keetch-Byram Drought Index, or KBDI (Keetch and Byram 1968), a drought indicator designed for forestry applications and widely used in the south-eastern United States. This application of the KBDI is similar in some respects to that employed by Griffiths (1999) and Noble *et al.* (1980) in calculating the drought factor for the McArthur Forest Fire Danger Meter (McArthur 1967). This study examines the relationship between the FFWI, a modified Fire Weather Index that includes rainfall (mFFWI) and fire history over a 20 year period (1981–2001) for Florida.

Methods

The FFWI is a non-linear filter of meteorological data designed to provide a linear relationship between the

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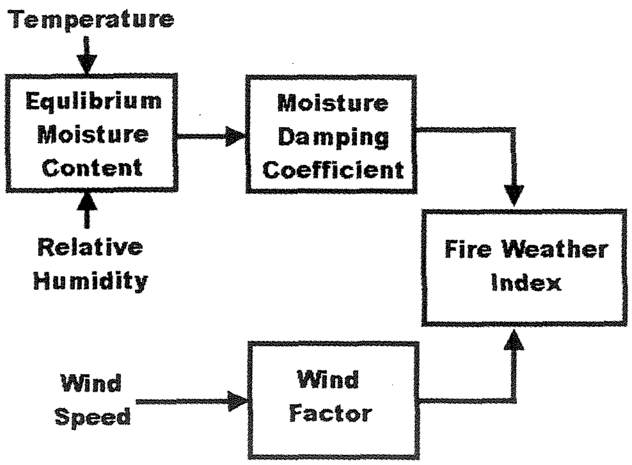

Fig. 1. Schematic of Fosberg Fire Weather Index (Fosberg 1978).

combined weather inputs and wildland fire behavior. The flame length model of Byram (1959) is considered linearly related to fire suppression efforts and is the basis of the Burning Index of NFDRS (Deeming *et al.* 1972). Fosberg (1978) uses these same principles to derive the FFWI with the assumption that fuel bed properties such as surface area to volume ratio and moisture of extinction are fixed in both space and time. This flame length formulation is essentially divided into a fuel moisture component and a rate of spread component (Fig. 1). The rate of spread component is based on the Rothermel (1972) model while the fuel moisture component is the equilibrium moisture content as determined by Simard (1968). The FFWI is given by:

$$FFWI = \eta\sqrt{1+U^2}/0.3002, \tag{1}$$

where U is the wind speed in miles per hour. The moisture damping coefficient, η, is given by

$$\eta = 1-2(m/30)+1.5(m/30)^2-0.5(m/30)^3. \tag{2}$$

The equilibrium moisture content (m) is given as a function of temperature in degrees Fahrenheit (T) and relative humidity in percent (h):

$$m = \begin{cases} 0.03229+0.281073h-0.000578hT \\ \quad \text{for } h<10\% \\ 2.22749+0.160107h-0.01478T \\ \quad \text{for } 10\% < h \le 50\% \\ 21.0606+0.005565h^2-0.00035hT-0.483199h \\ \quad \text{for } h>50\%. \end{cases} \tag{3}$$

The fuel bed properties used by Fosberg in the development of the index require some further explanation.

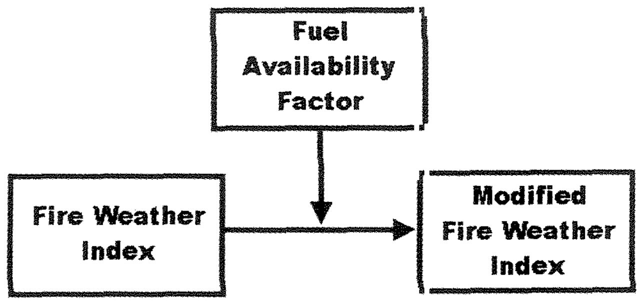

Fig. 2. Schematic of Modified Fosberg Fire Weather Index.

These properties do not reflect any one particular fuel model from either NFDRS or the Fire Behavior Prediction System. Instead, Fosberg assumed the fuels to be extremely fine (surface area to volume ratio of 3000 ft^{-1}, the highest ratio of any fuel model in the 1978 NFDRS) with a moisture of extinction value of 30% (also the highest value of any of the 1978 NFDRS models). The resultant hybrid fuel model is more volatile than any of the other NFDRS fuel models.

In this study, a dependence on precipitation is added to the FFWI through the addition of a 'fuel availability' factor, or FAF (Fig. 2). The FAF is defined as a function of the KBDI, which is in turn a function of maximum daily temperature, daily precipitation, and annual average precipitation. In the 1988 revision of the 1978 NFDRS (Burgan 1988), the KBDI was added as a drought factor that controlled the addition of a 'drought fuel' load to the system as drought intensified. This drought fuel load was fuel model specific and was added in an attempt to improve the response of NFDRS to drought in more humid climates, such as the south-eastern United States. In the present study, the KBDI will be used to scale the FFWI to reflect total fuel availability, rather than just the addition of a drought fuel load.

Table 1 presents the fuel loadings for the fuel models of the 1988 Revision of NFDRS. The FAF will be based on the average fuel loading from these models. At a KBDI of 0 it is assumed that only the 1-hour and 10-hour timelag fuel loads are available, while at a KBDI of 800 the entire fuel load is available. To produce a non-dimensional quantity, these values are scaled by the sum of the 1-, 10- and 100-hour fuel loads. The FAF function is defined by a second-order polynomial fit through three points: KBDI = 0, FAF = 0.72; KBDI = 800, FAF = 2.1; KBDI = 450, FAF = 1). This last point represents an FAF of 1 when the KBDI is at its annual statewide mean as determined from 50 years of temperature and precipitation data. The resulting equation for the FAF as a function of KBDI (K) is

$$FAF = 0.000002K^2 + 0.72. \tag{4}$$

This form for the FAF was chosen to provide a continuous function that allows the fuel availability to increase rapidly as drought conditions become more severe (Fig. 3). The

Table 1. Fuel loadings for 1988 NFDRS fuel models (tons per acre)

Fuel model	1 hour	10 hour	100 hour	1000 hour	Woody	Herbaceous	Drought
A	0.20	0	0	0	0	0.30	0.20
B	3.50	4.00	0.50	0	11.50	0	3.50
C	0.40	1.00	0	0	0.80	0.80	1.80
D	2.00	1.00	0	0	3.00	1.00	1.50
E	1.00	0.50	0.25	0	1.00	0.50	1.50
F	2.50	2.00	1.50	0	7.00	1.00	2.50
G	2.50	2.00	5.00	12.00	0.50	0.50	5.00
H	1.50	1.00	2.00	2.00	0.50	0.50	2.00
I	12.00	12.00	10.00	12.00	0	0	12.00
J	7.00	7.00	6.00	5.50	0	0	7.00
K	2.50	2.50	2.00	2.50	0	0	2.50
L	0.25	0	0	0	0	0.50	0.25
N	1.50	1.50	0	0	2.00	0	2.00
O	2.00	3.00	3.00	2.00	7.00	0	3.50
P	1.00	1.00	0.50	0.00	0.50	0.50	1.00
Q	2.50	5.40	2.90	1.00	3.00	1.00	3.50
R	0.50	0.50	0.50	0.00	0.50	0.50	0.50
S	0.50	0.50	0.50	0.50	0.50	0.50	1.50
T	1.00	0.50	0	0	2.50	0.50	1.00
U	1.50	1.50	1.00	0	0.50	0.50	2.00
Average	2.29	2.35	1.78	1.88	2.04	0.43	2.74

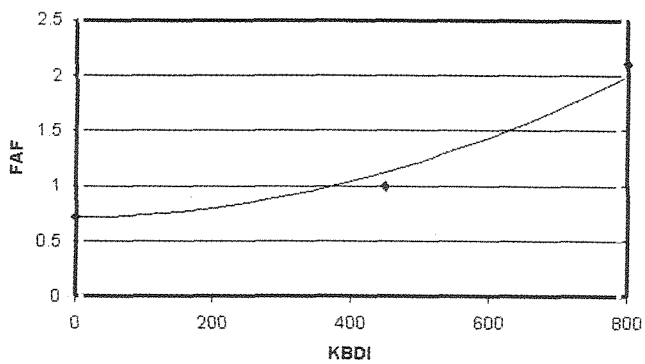

Fig. 3. Fuel availability factor (FAF) as a function of KBDI.

modified FFWI (hereafter referred to as the mFFWI) is simply calculated by multiplying the FFWI (equation 1) by the fuel availability factor (equation 4):

$$mFFWI = FAF * FFWI. \quad (5)$$

Using the KBDI to determine the fuel availability factor is similar in concept to the use of the KBDI in calculating the drought factor for the McArthur fire danger meter as described by both Griffiths (1999) and Noble *et al.* (1980). While both the fuel availability factor and the drought factor are used as multipliers to achieve the final index value, their dependence on the KBDI is considerably different. The drought factor asymptotically approaches its maximum value, in much the same way that the KBDI itself approaches its maximum value of 800. The greatest change in the drought factor occurs at low to intermediate values with relatively little change at high values of the KBDI. The fuel availability factor, however, increases most rapidly as the KBDI approaches its maximum.

Since the KBDI is a once per day calculation, using it to modify the FFWI may appear to adversely impact one of the strengths of the FFWI, the ability to assess short-term, local variations in potential fire behavior. However, only the drying phase of the KBDI is truly restricted to once a day calculation as it is a function of the maximum daily temperature and annual average rainfall. The wetting portion of the KBDI calculation, a simple subtraction of the rainfall (in inches) multiplied by 100, can be updated with hourly rainfall information if desired. The only complication in using hourly rainfall observations lies in making certain that the KBDI's rainfall threshold of 0.20 inches is achieved prior to reducing the index value.

Weather data for this study were compiled from 120 National Weather Service observing sites for the period of January 1981 through June of 2001. This dataset provided the information required for the FFWI calculation, temperature (maximum), relative humidity (minimum) and wind speed (daily average). While these data are not optimal for displaying the spatial and temporal information that the FFWI is specifically designed for, it is sufficient to compare the FFWI and mFFWI in a more traditional fire danger rating scheme, which is all that the historical fire database used in this study can support. Daily activity reports from the Florida Division of Forestry that summarize the number of fires and area burned by forestry district are used as the fire database for this study. It is important to note that only days on which there were active fires are considered for this study. The

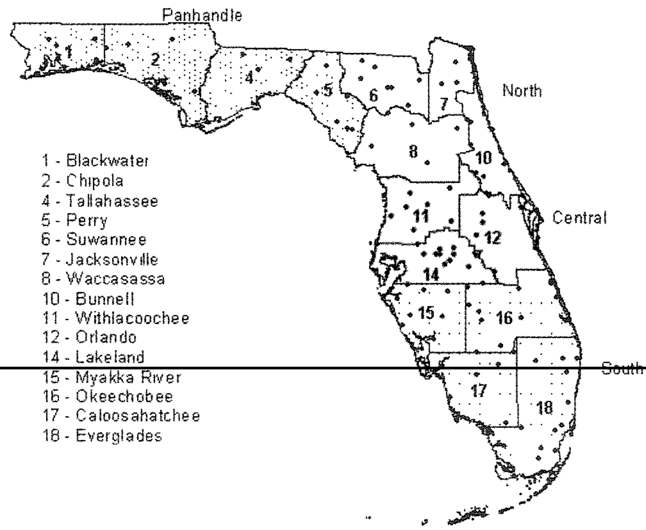

Fig. 4. Map showing the location of 120 National Weather Service observing stations (dots) and Florida's 15 Forestry districts (numbers reflect the Division's current fire reporting system).

reader is referred to Fig. 4 for district boundaries and weather station locations.

Results and discussion

An examination of the mFFWI formulation reveals that it should lead to a broadening of the potential response of the FFWI for differing values of the fuel availability factor. Figure 5 highlights the broad range of possible mFFWI values for a given value of the FFWI depending upon variations in the KBDI. The slope of the regression line fit to these data (1.2266) can be viewed as an approximate mean fuel availability factor that corresponds to a KBDI value of 503, which is slightly higher than the long-term mean KBDI (449) that was used in the formulation of the FAF. The mean

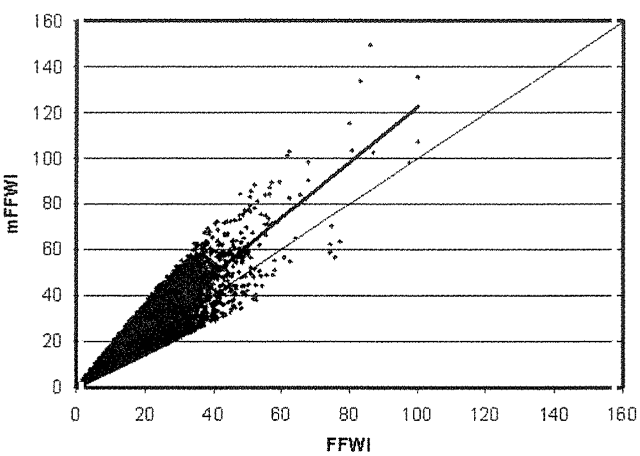

Fig. 5. Comparison of Fosberg Fire Weather Index (FFWI on horizontal axis) and the modified form given in equation (5) (mFFWI on vertical axis). Equation for trend line is $y = 1.2266x+0.5495$. (Based on 22 528 points.)

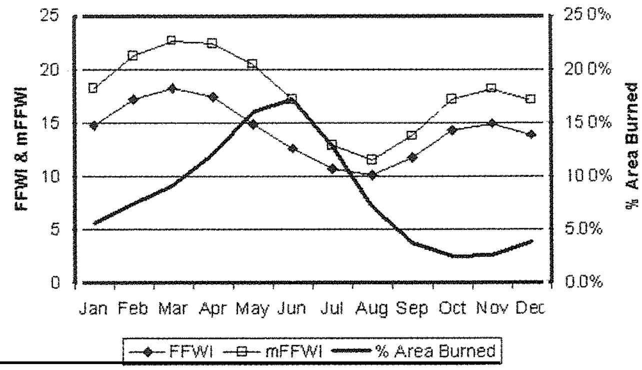

Fig. 6. Monthly average values for FFWI, mFFWI and percentage area burned.

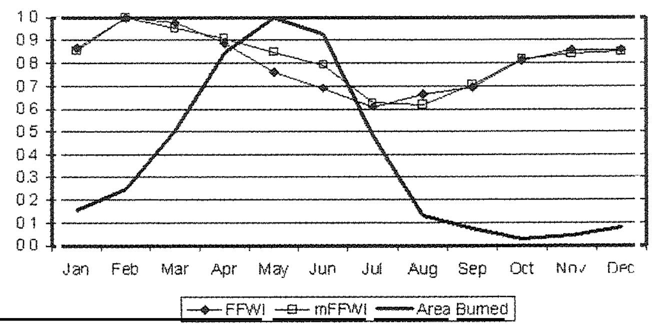

Fig. 7. Scaled standard deviations for FFWI, mFFWI and area burned.

KBDI for the period of the fire data used in the analysis is 511, very close to that obtained from the regression slope.

Florida primarily has a spring fire season with the majority of the area burned occurring during May and June. This peak in burning does not coincide with the peaks in monthly mean FFWI or mFFWI (Fig. 6). The peaks in the fire weather indices occur during early spring and fall. At these times of year, cold frontal passages bringing dry air and strong winds are more frequent and lead to elevated monthly mean values of the fire weather indices. Note that the mFFWI does have a broader spring peak as the FAF tends to correlate well with area burned ($r = 0.77$).

May and June are the months that exhibit the most variability in area burned and these are the key months in determining whether Florida experiences a severe fire season. In an ideal world the fire weather indices should also exhibit strong variability at this time of year; however, examination of the monthly standard deviations for the fire weather indices and area burned reveals that the peak standard deviation for the fire weather indices occurs in February rather than May when the peak standard deviation for area burned occurs (Fig. 7). The mFFWI does show a relative increase in the monthly standard deviations in the May and June periods. Note that in Fig. 7 the standard

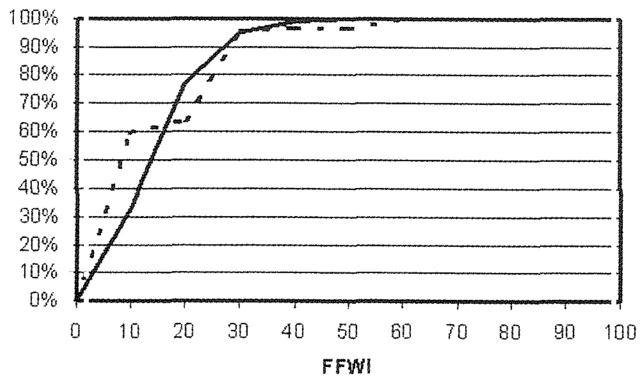

Fig. 8. Cumulative frequency plot for percentage of days (solid) and area burned (dotted) as a function of FFWI.

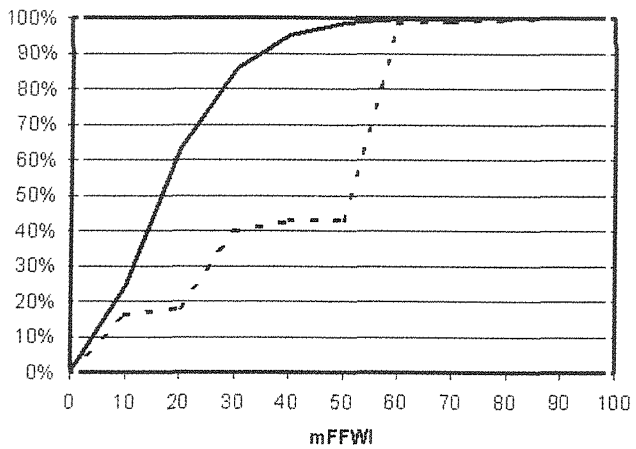

Fig. 9. Cumulative frequency plot for percentage of days (solid) and area burned (dotted) as a function of mFFWI.

deviation for each variable was scaled by its maximum value to facilitate plotting on a common axis.

Examination of a cumulative frequency graph for the number of days the FFWI is in a given 10 point range (solid) and the percentage area burned while the FFWI is in that same range (dotted) is shown in Fig. 8. The FFWI is less than 20 for 95% of the time, which does not indicate very severe burning conditions, yet 64% of the area burned between 1981 and 2000 occurred when the FFWI was less than 20. This would tend to suggest that the FFWI may not be an effective indicator of fire potential in Florida. Figure 9 displays similar information except that the mFFWI replaces the FFWI. For the mFFWI, 97% of the observations were for values below 50, but these days accounted for only around 44% of the acreage burned. The remaining 56% of the area burned on the remaining 3% of the days when the mFFWI was above 50, indicating more severe burning conditions.

Examination of Fig. 9 reveals some useful breakpoints for establishing some basic classes for assessing the potential weather impacts on wildland fires (Table 2). Values of the

Table 2. mFFWI classification based on percentage area burned

mFFWI Class	mFFWI (% year)	% Area Burned
Low	<25 (48%)	16%
Moderate	25–49 (49%)	28%
High	>50 (3%)	56%

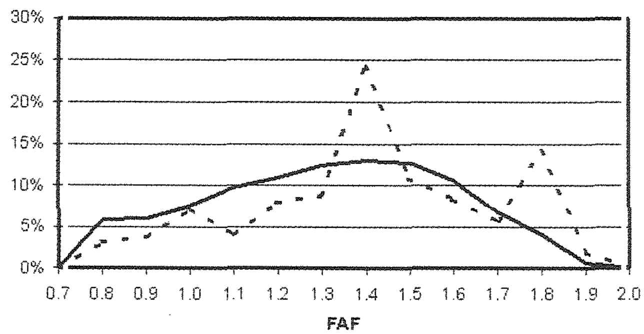

Fig. 10. Frequency distribution for percentage of days (solid) and area burned (dotted) as a function of FAF.

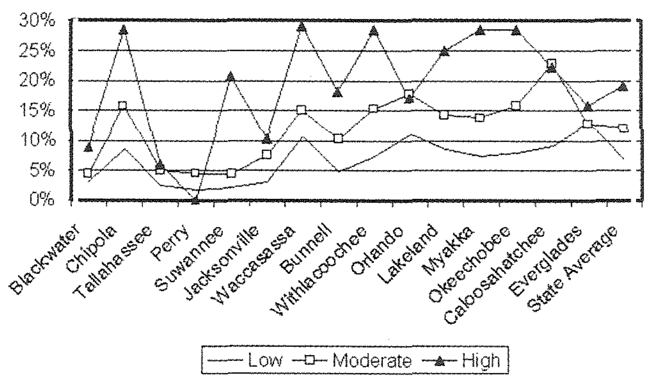

Fig. 11. Probability of above-average area burned by mFFWI class.

mFFWI below 25 occurred 48% of the time during the study, but accounted for only 16% of the area burned. This will be considered low fire potential. The moderate classification, values from 25 to 49, occurred 49% of the time and represented a slightly larger portion of the total area burned, 28%. The high category, values greater than 50, occurred 3% of the time and accounted for the remaining 56% of the area burned. The three main jumps in the cumulative frequency plot for the area burned as a function of the mFFWI in Fig. 9 appear to be related to local maxima in the frequency distribution of percentage area burned as a function of the FAF (Fig. 10).

Using the breakpoints and classes established above, the probability of above-average fire activity for each class is examined. The average daily area burned on days with active fires per district was 92 acres (37.23 ha). Figure 11 displays

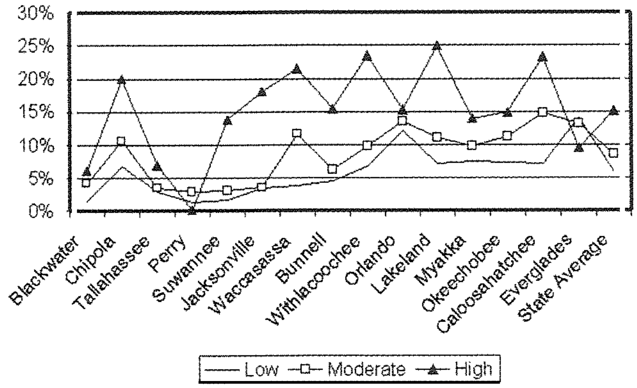

Fig. 12. Probability of above-average area burned by FFWI class.

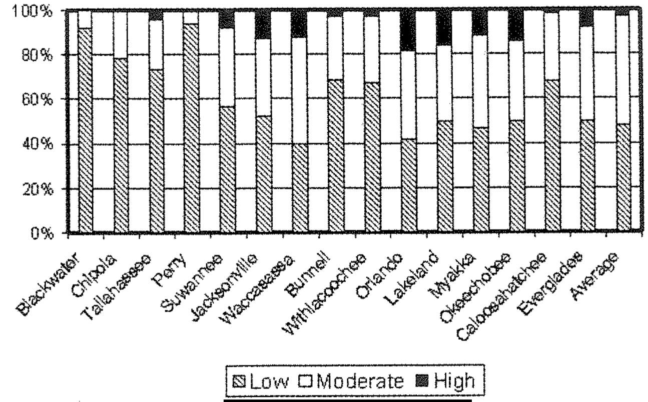

Fig. 13. Percentage of days each district was in each mFFWI category and the normal percentages described in Table 1.

the probability of above average area burned for each class by district. In general, the high mFFWI class shows a much higher probability for the occurrence of above-average area burned than the low class. The most notable exception to this is the Perry district, which shows a zero probability due to no joint occurrences of above average fire activity and high mFFWI. The saw tooth pattern evident in the middle portion of Fig. 11 for the high class reflects some spatial variability as the districts with the peak values tend to be on the western half of the peninsula while the low values tend to be on the eastern half. The predominant wind direction throughout the peninsula of Florida is easterly for much of the year, bringing elevated moisture levels, and therefore lower mFFWI values, to the eastern half of the peninsula where the marine influence is most pronounced.

The probability of above-average fire activity for similar classes of the FFWI is shown in Fig. 12. Breakpoints for these classes were determined by taking the breakpoints for the mFFWI and converting them to FFWI values using the slope of the regression line in Fig. 5 (1.2266) as a fuel availability factor in equation (5). The resulting breakpoints for the FFWI are: Low <20, Moderate $\geq$ 20 and <40 and High $\geq$ 40. The differences between Figs 11 and 12 are fairly subtle, which is not completely unexpected as fire size is largely a factor of wind speed which is accounted for by both indices.

Data from January through June of 2001 are used to further examine the value of the identified breakpoints. Fire data and weather data for each of the Florida Division of Forestry's 15 districts are used to assess which area had the most severe fire conditions during the period as determined by the mFFWI. The percentage of time during the period when the mFFWI was in each of the three categories defined in Table 2 is shown in Fig. 13. The districts in the panhandle of Florida (Blackwater, Chipola, Tallahassee and Perry) show an above normal percentage of low mFFWI days with few to no high mFFWI days. In contrast the central part of the state (Lakeland and Orlando districts) show a much higher than normal percentage of high mFFWI days.

Table 3. Top five districts ranked by % days of high mFFWI

District	% High mFWI	% Total Area Burned
Orlando	18.5	5.5
Lakeland	15.7	14.7
Okeechobee	14.3	39.5
Jacksonville	13.1	0.5
Waccasassa	12.7	1.6

Table 3 shows the five districts with the highest percentage of high mFFWI days and the percentage of acres burned statewide that were in each of these districts. The top three districts (Orlando, Lakeland and Okeechobee) averaged over 5 times the normal percentage of high mFFWI days and accounted for nearly 60% of the acreage burned during 2001. The only district with a significant percentage of acreage not listed in Table 3 is the Everglades district, where 21.4% of the acreage burned. The percentage of high mFFWI days in Everglades was 7.9%, more than double the normal percentage of 3. All but 4 of the 15 districts had above-normal percentages of high mFFWI days, reflecting the prolonged drought and above-average values for the fuel availability factor.

Summary and Conclusions

A simple modification that accounts for variability in rainfall/drought has been added to the Fosberg Fire Weather Index in the form of a fuel availability factor. This factor is calculated as a function of the Keetch-Byram Drought Index, which is commonly used in forestry applications. A comparison of the original and modified fire weather indices for a 20 year period in Florida shows that the modified index provides a slightly more useful measure of fire potential, as clear breakpoints in area burned as a function of the index were easily discernable. Application of the modified Fire Weather Index for the 2001 fire season reinforced the new index's ability to highlight geographic variations in fire danger as the three districts with the highest percentage of high mFFWI days accounted for almost 60% of the area burned in the state.

The purely meteorological nature of the mFFWI lends itself well to the development of forecast products based on gridded weather data from a numerical weather prediction model. Gridded products based on the FFWI are commonly produced by various modeling groups and the addition of the fuel availability factor would require only some minor modifications to the algorithms that produce these products. By adding the influence of rainfall, the mFFWI will be able to reveal the impact of dry versus wet cold fronts on fire potential. While the FFWI would show high values due to strong winds and low humidity behind a front, the mFFWI would slightly moderate these values in the event of a wet frontal passage as the rainfall reduces the fuel availability factor. The Florida Division of Forestry plans to implement the modified form of the Fosberg Fire Weather Index as part of its routine products from the MM5 model.

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